The NOνA Experiment

(NuMI Off-Axis ν_e Appearance)

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Fermilab

NO-VE 2006

Neutrino Oscillations in Venice

7 February 2006

(For the Collaboration)

Outline for Talk

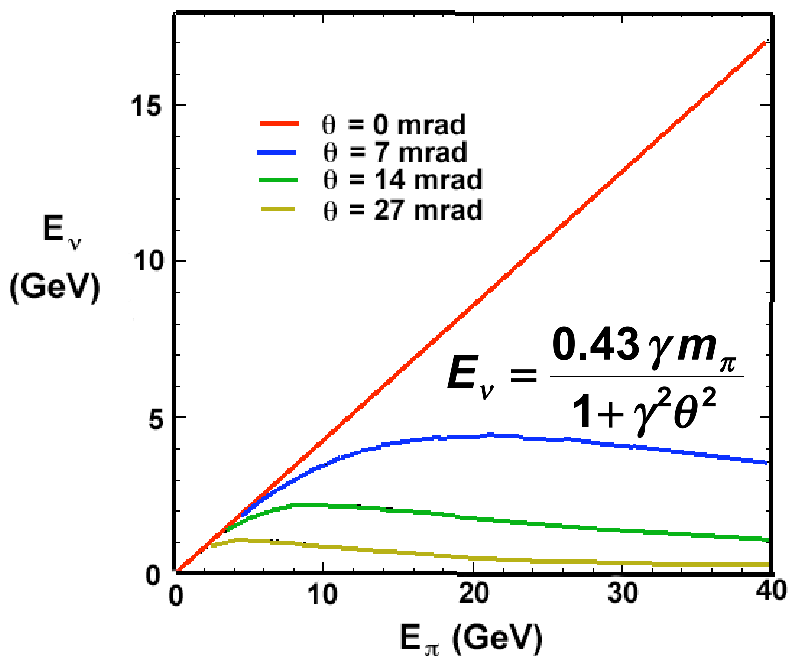
- Physics Goals:
  - A developing, staged program:
    - θ_{13} (ν_e Appearance)
    - Sign of Δm^2
    - CP-Violation
- The NOνA detector:
  - Size, structure, resolution
  - Comparison to MINOS
  - Near detector
- Simulations and Backgrounds:
  - What is done and what is underway
- Status, Cost & Schedule

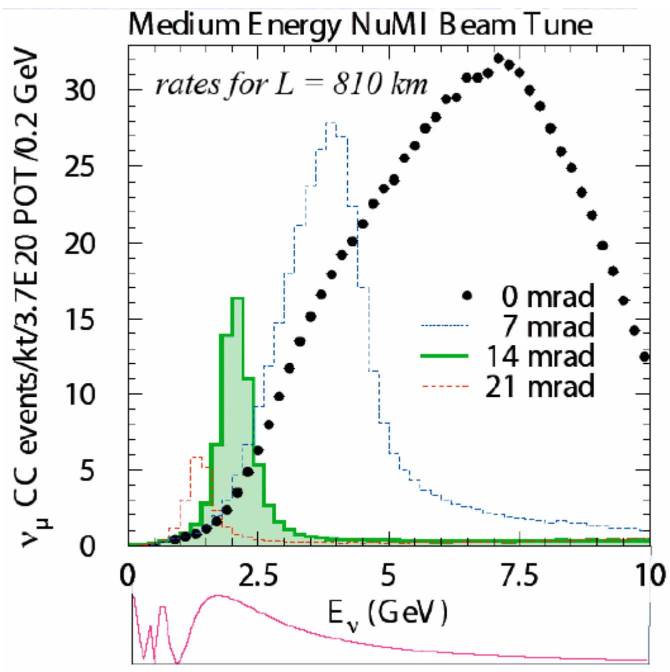
Current Ideas & Goals

- Phase 1 (Extend $\nu_\mu \rightarrow \nu_e$ reach by order of magnitude; explore mass hierarchy & CPV)
  - NOvA
  - T2K (Kajita and Nishikawa)
  - Reactors: θ_{13} (Laserre)
- Phase 2 (Extend reach for mass hierarchy & CPV)
  - NOvA + PD (Geer)
  - HK + PD
  - Brookhaven VLBL proposal
- CERN PD + Mton H2O detector
- Phase 3 (Significantly extend reach)
  - Neutrino factory
  - Beta beam

NuMI Off-Axis

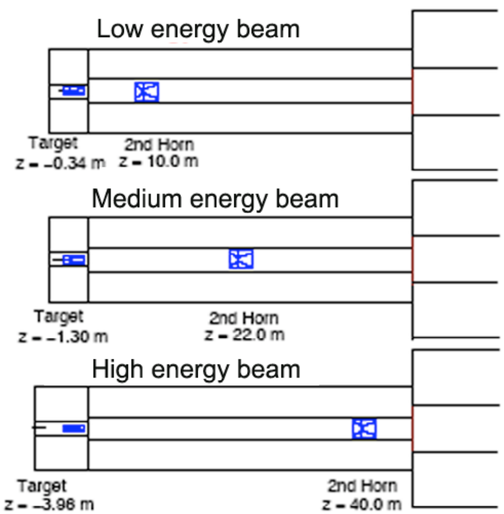
- 15 mrad off axis & 810 km from the source
- Yields a narrow band beam on oscillation maximum
- More flux & reduced backgrounds from the HE tails

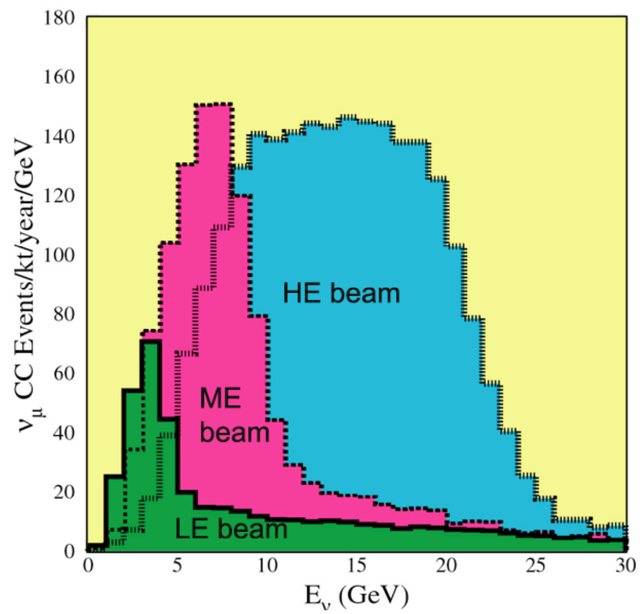




NuMI Beam

- Move Horn toward/away from target:





cross-section included

Rates and Spectra

- Spectra for NuMI Medium Energy Beam:

Source of π^o's to be cut

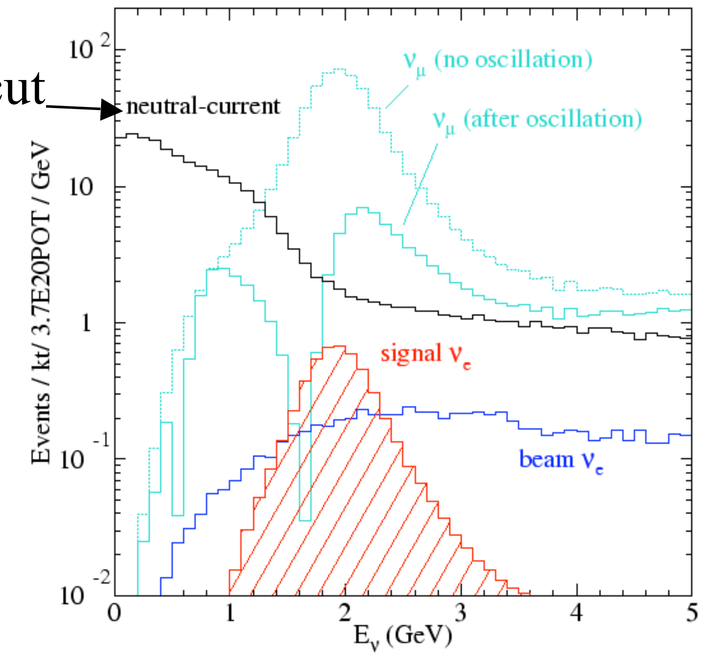


Fig. 2.8: Simulated energy distributions for the ν_e oscillation signal, intrinsic beam ν_e events, neutral-current events and ν_μ charged-current events with and without oscillations. The simulation used $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\sin^2(2\theta_{23}) = 1.0$, and $\sin^2(2\theta_{13}) = 0.04$. An off-axis distance of 12 km at 810 km was assumed.

$P(\nu_\mu \rightarrow \nu_e)$ in Vacuum

$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$
\begin{aligned}
P_1 &= \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(\Delta m^2_{13} \frac{L}{E}) \\
P_2 &= \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(\Delta m^2_{12} \frac{L}{E}) \\
P_3 &= \mp J \sin(\delta) \sin(\Delta m^2_{13} \frac{L}{E}) \\
P_4 &= J \cos(\delta) \cos(\Delta m^2_{13} \frac{L}{E})
\end{aligned}
$$

Atmospheric

Solar

Atmospheric-solar interference

where

$$
\begin{aligned}
J &= \sin(2\theta_{13}) \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{23}) \\
&\quad \times \sin(\Delta m^2_{13} \frac{L}{E}) \sin(\Delta m^2_{12} \frac{L}{E})
\end{aligned}
$$

- note terms with Δm_{13} and δ mix, hence matter-CP ambiguity

$P(\nu_\mu \rightarrow \nu_e)$ (in Matter)

- In matter at oscillation maximum, P_1 will be approximately multiplied by $(1 \pm 2E/E_R)$ and P_3 and P_4 will be approximately multiplied by $(1 \pm E/E_R)$, where the top sign is for neutrinos with normal mass hierarchy and antineutrinos with inverted mass hierarchy

$$E_R = \frac{\Delta m_{13}^2}{2\sqrt{2}G_F\rho} \approx 11 \text{ GeV for the Earth's crust}$$

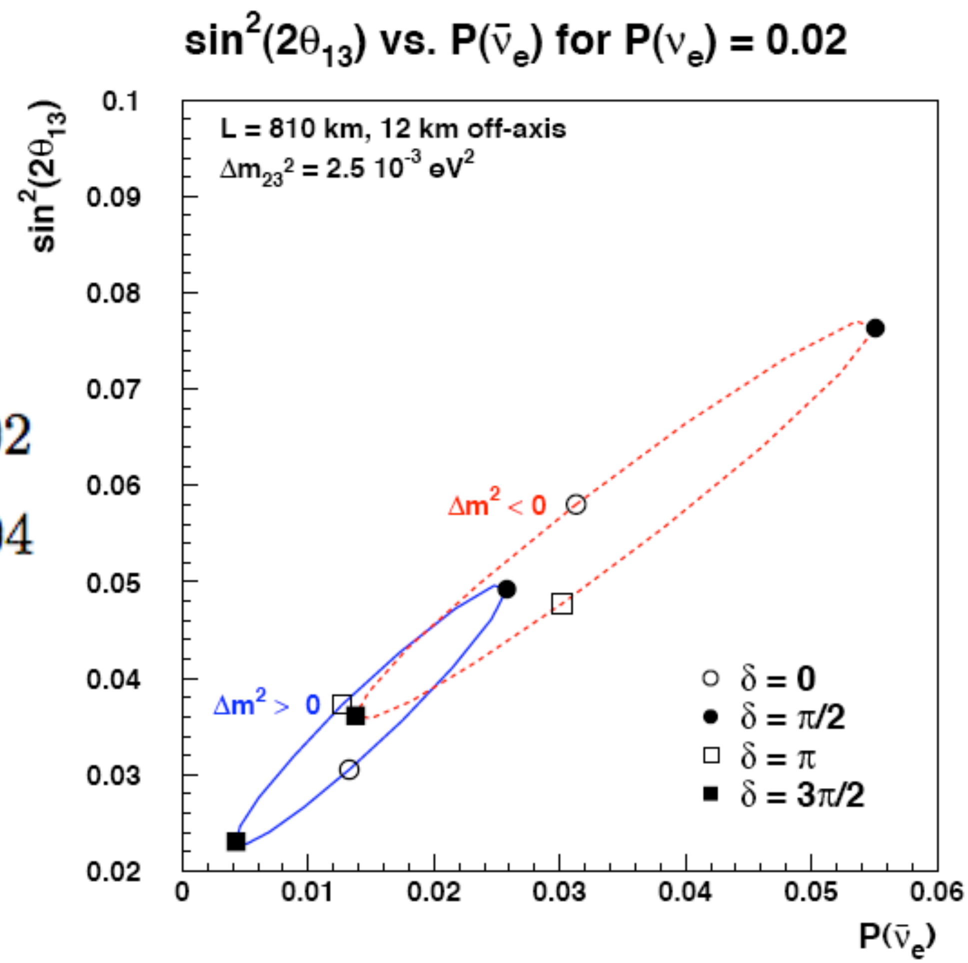
  - About ±30% effect for NuMI/NovA
  - About ±11% effect for T2K
- The effect is reduced for energies above the oscillation maximum & increased for energies below

Ambiguity between Mass Ordering and CP Phase

- Need ν and $\bar{\nu}$
- Ambiguity depending on sign of Δm^2, δCP
- Statistical Errors

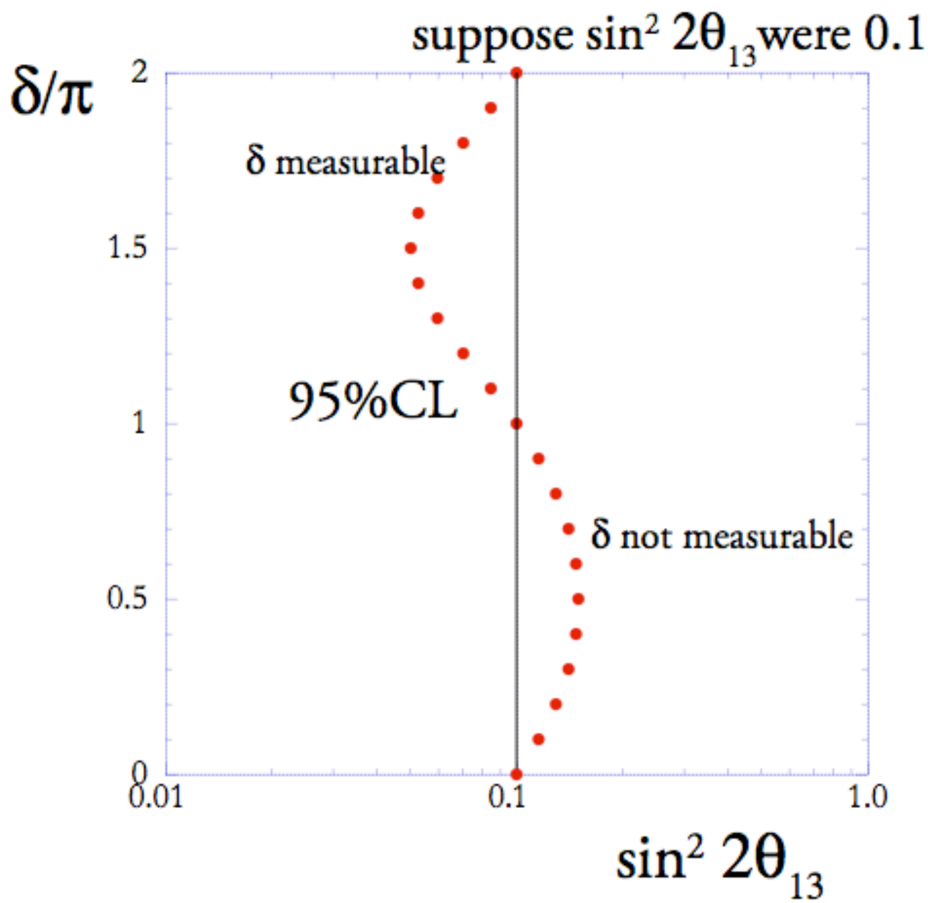
$$P(\bar{\nu}_e) = 0.02 \pm 0.002$$
$$\sin^2\theta_{13}(\nu) = 0.05 \pm 0.004$$

- More detail later
- Combining Nova and T2K also useful!

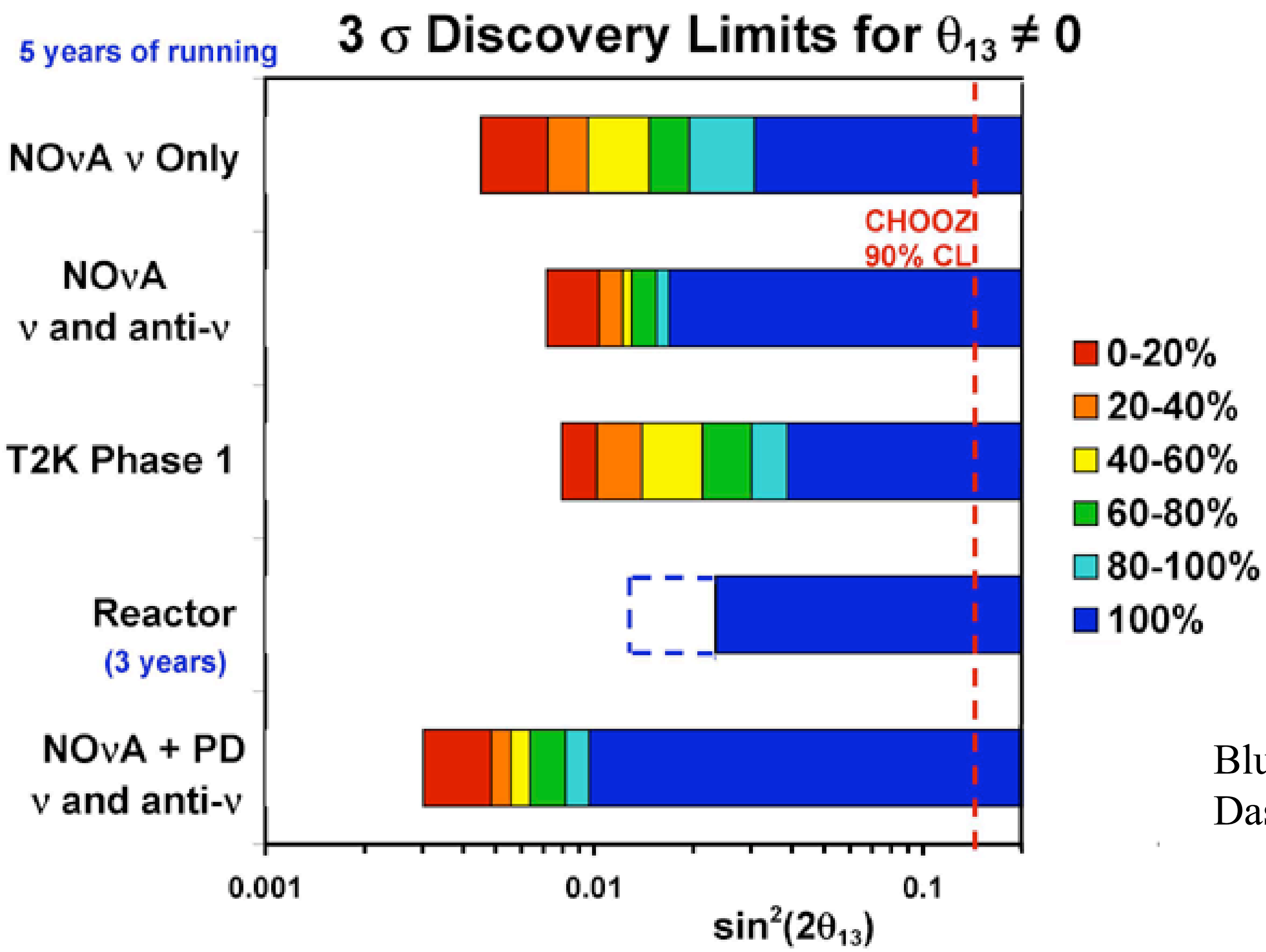


"Fraction of δ"

Fraction of δ: Above or below significance cutoff?



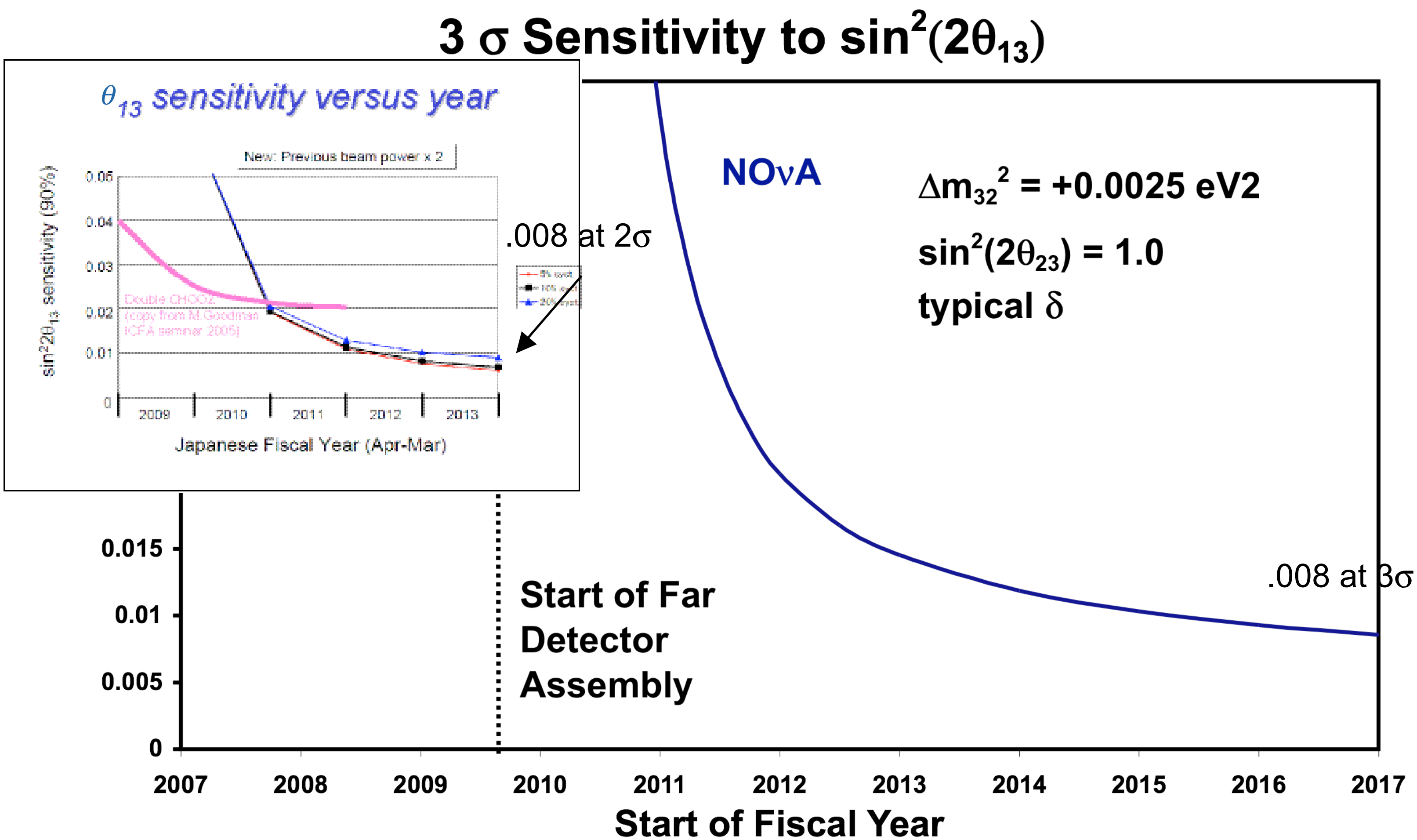
3 σ Sensitivity to $\theta_{13} \neq 0$



Fraction of δ covered

Blue "Reactor" is APS; Dashed is Braidwood

Sensitivity vs Time



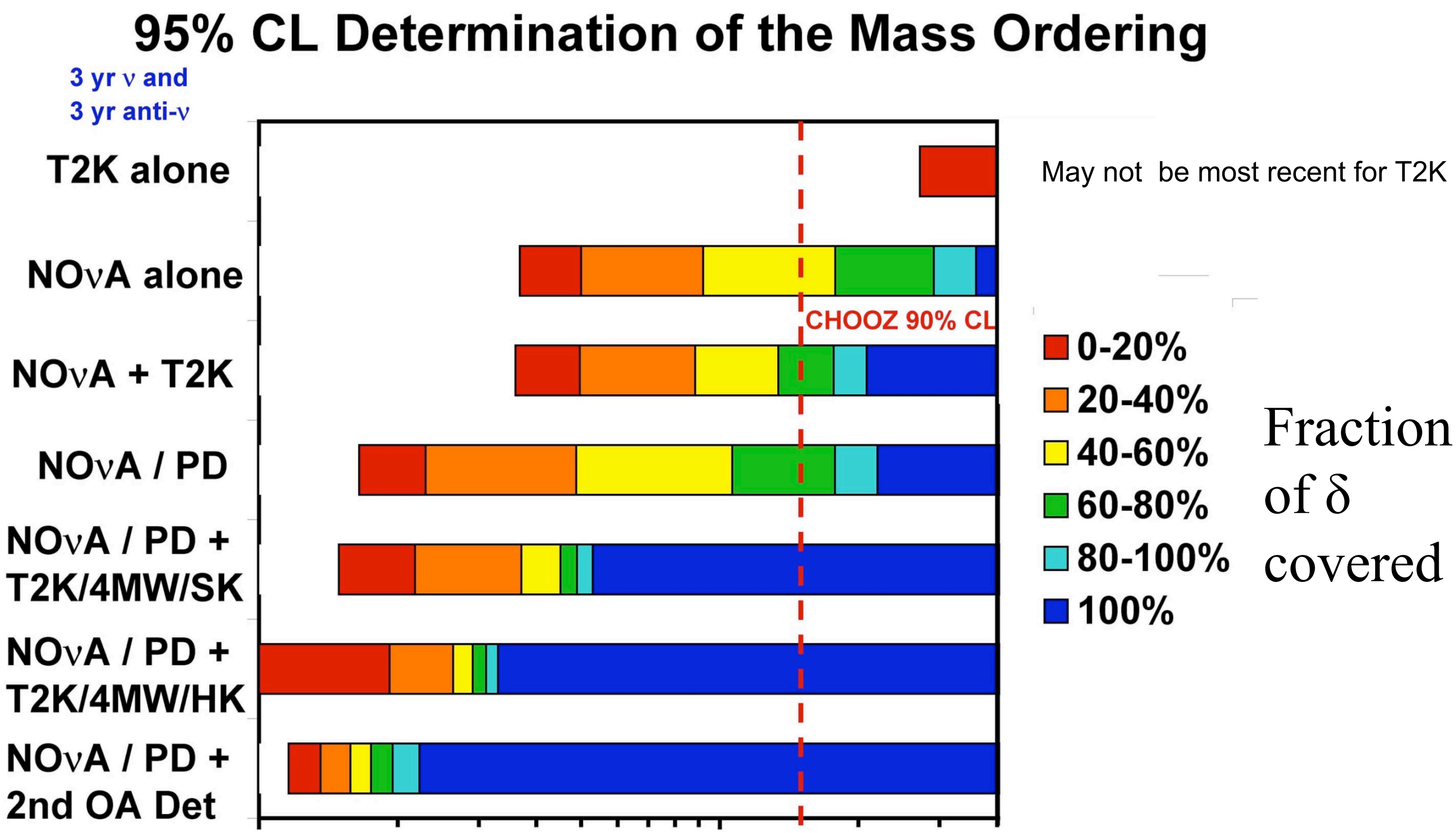
Importance of the Mass Ordering

- Window on very high energy scales
  - Grand unified theories (mostly) favor the normal mass ordering but other approaches favor the inverted ordering
- The next generation of neutrinoless double beta decay experiment care about the mass ordering
  - If inverted ordering, can decide if the neutrino is its own antiparticle
  - If normal ordering, a negative result is inconclusive
- For CPV measurement we need to resolve the mass ordering
  - Matter effects contributes an apparent CP violation that must be corrected

Role of NOνA in Resolving the Mass Ordering

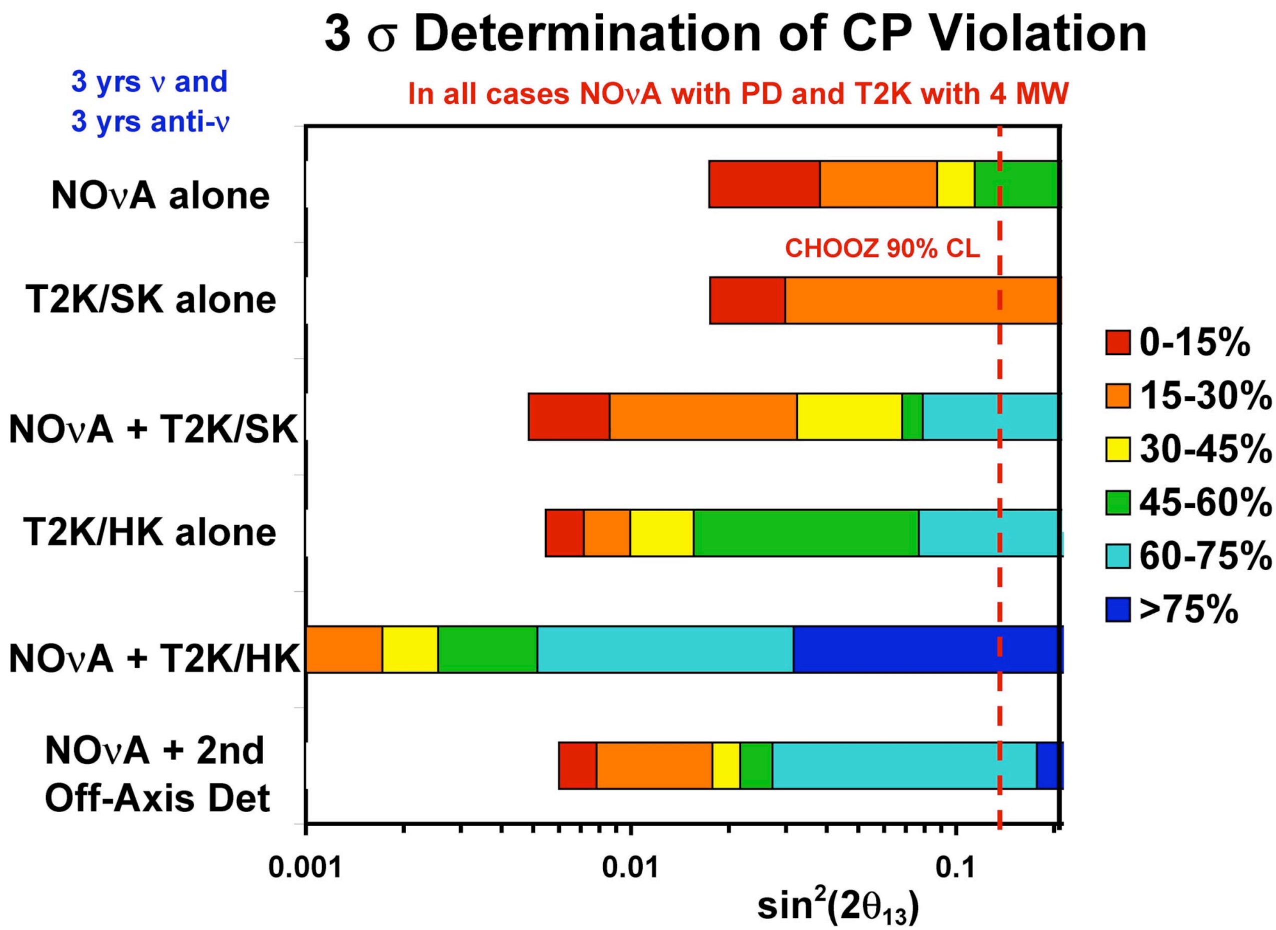
- The mass ordering can be resolved only by matter effects in the earth over long baselines
- NOνA is the only proposed experiment with a sufficiently long baseline to resolve the mass ordering
- The siting of NOνA is optimized for this measurement
- NOνA is the first step in a step-by-step program that can resolve the mass ordering in the region accessible to conventional neutrino beams

95% CL Resolution of the Mass Ordering



Fraction of δ covered

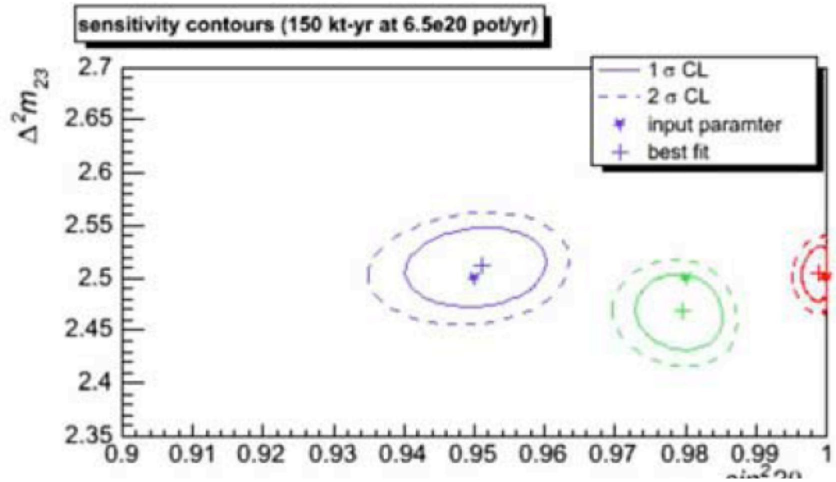
3 σ Determination of CP Violation



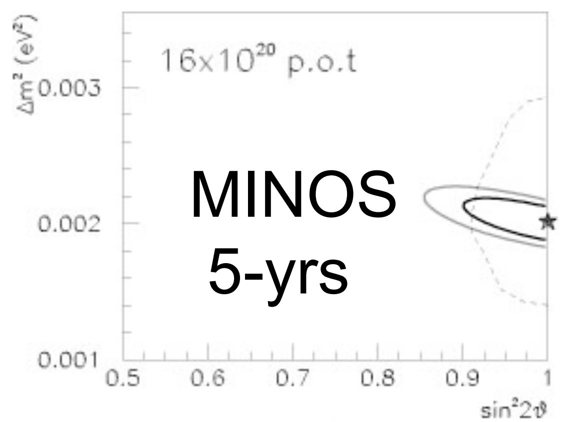
Fraction of δ covered

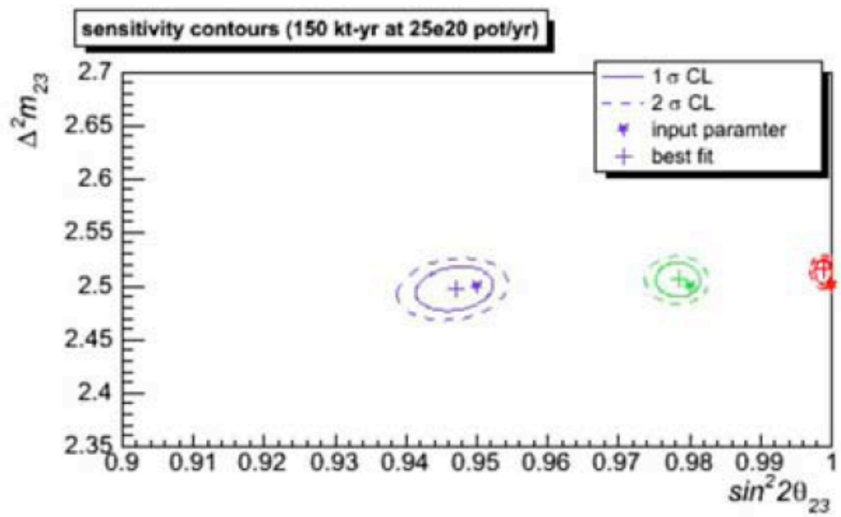
1. Must have measurement errors < 30° (3σ=90°)
2. Some values of δ (e.g. δ=0) not resolvable

Measurement of Δm_{32}^2 and $\sin^2(2\theta_{23})$



5-year ν run





5-year ν run
with Proton Driver

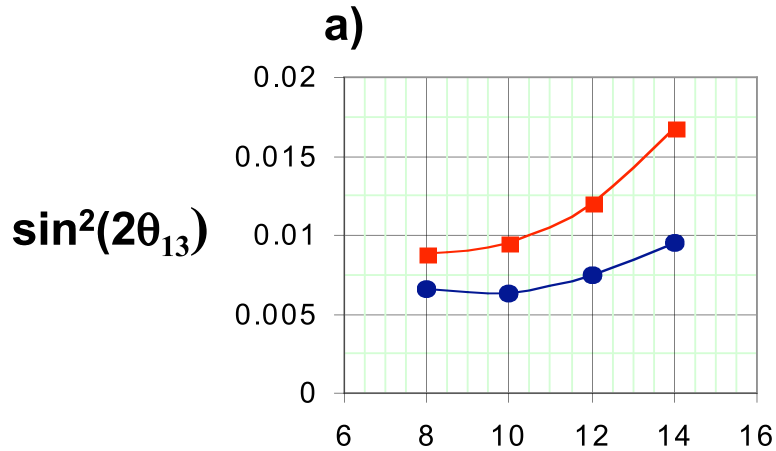
Sensitivity to Off-Axis Distance

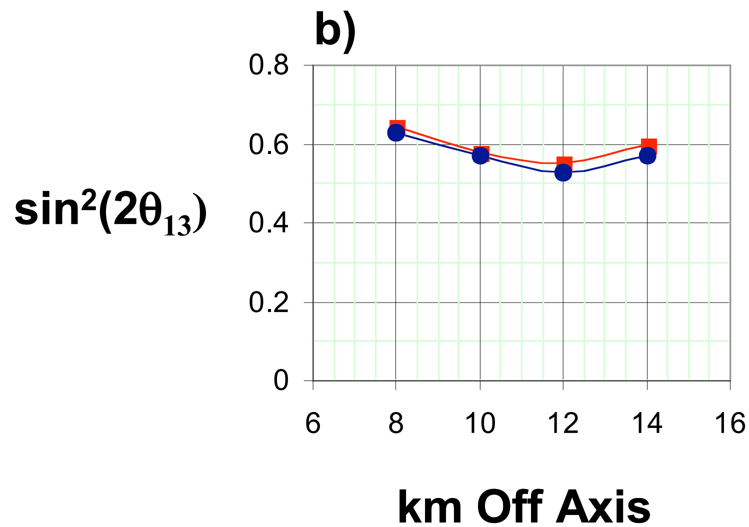
- 3 standard deviation discovery limit of NOνA for $\nu_\mu \rightarrow \nu_e$ oscillations as a function of $\sin^2(2\theta_{13})$ and the off-axis distance.

- 95% confidence level for NOνA to resolve the mass hierarchy as a function of $\sin^2(2\theta_{13})$ and the off-axis distance.

(new info from Parke?)

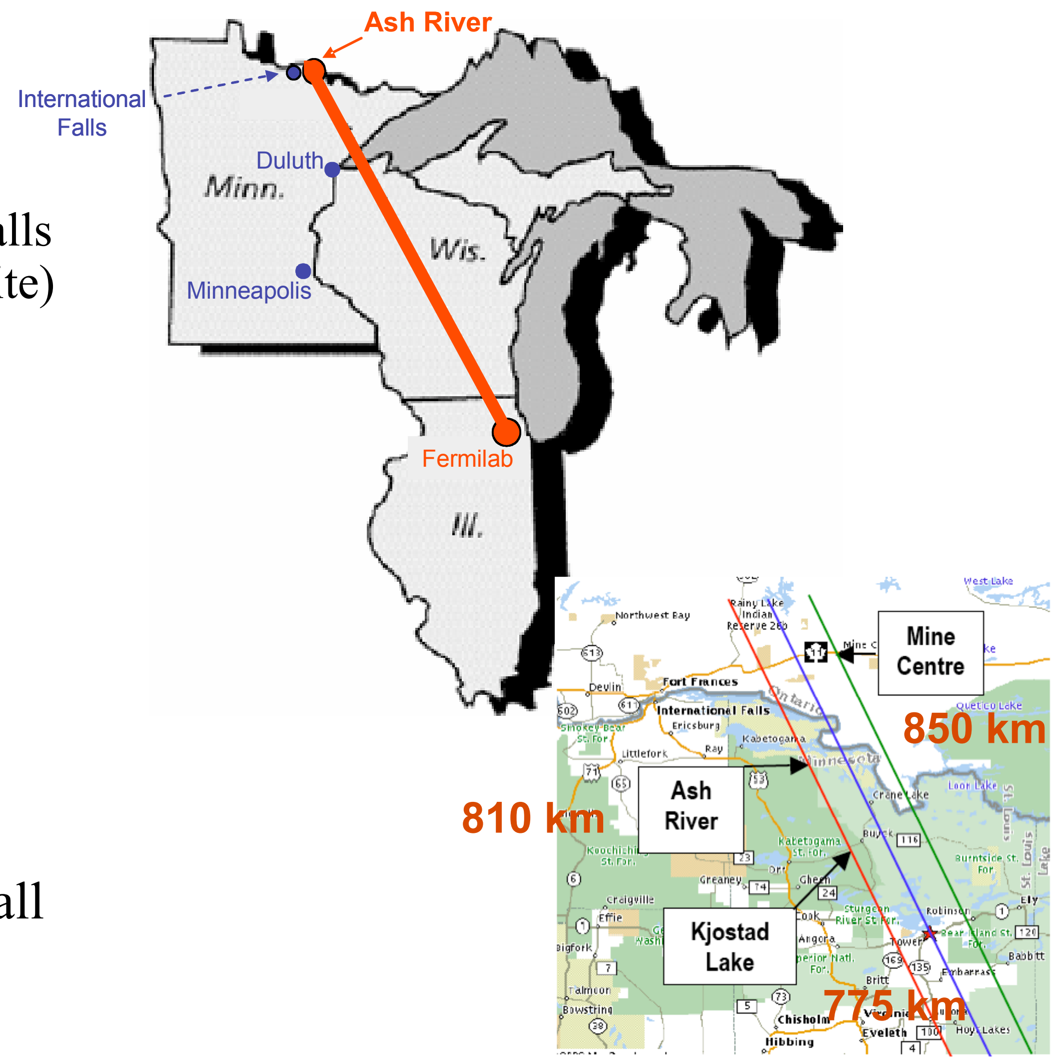
red normal, blue inverted





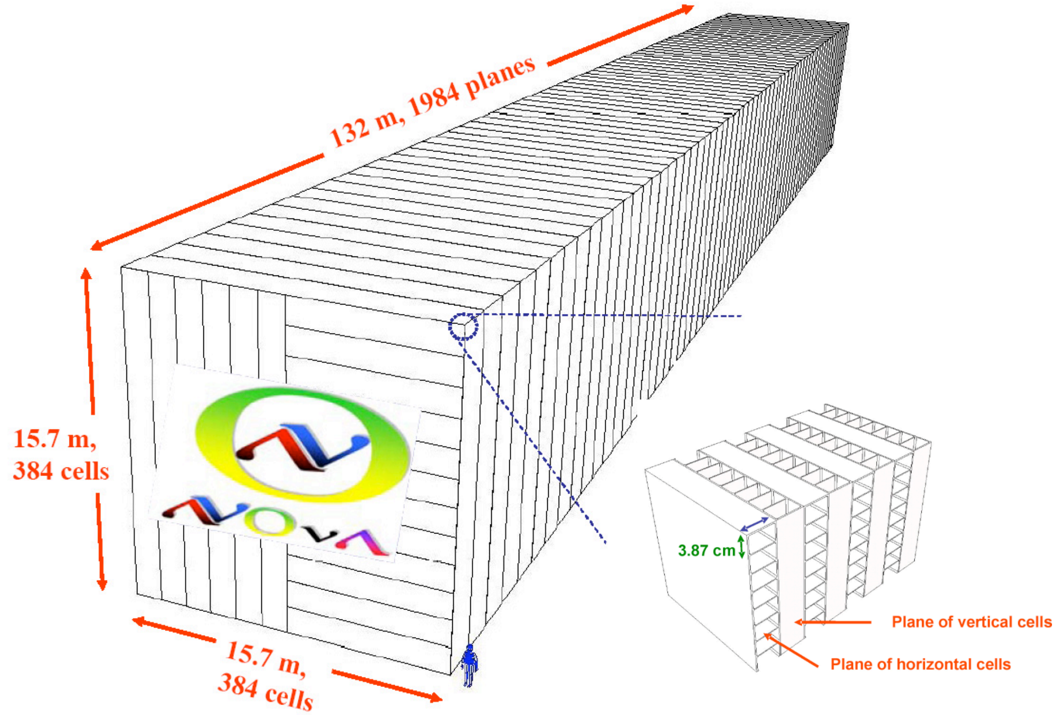
Far Detector Site

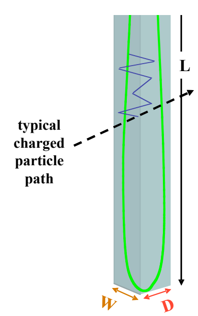
- Ash River
  - Baseline site
  - Can fly into International Falls (less than an hour drive to site)
  - Resort area
- Kjostad Lake
  - Orr-Buyck Rd
  - Good backup site
- Mine Centre
  - Must cross the US-Canada border (in a paper mill site) to get from airport to site
- Range of angles available at all sites



NOνA Far Detector

- Revised Proposal (April 05)
  - “Totally Active” scintillator detector (75%)
- 30 kT
  - 24 kT liquid scintillator
  - 6 kT of cells
- Liquid scintillator cells
  - 3.9 cm x 6 cm x 15.7m
  - 0.15 X_0 sampling
  - 1984 planes of cells
- Cell walls
  - Extruded rigid PVC
  - 3 mm outer; 2 mm inner horizontal; vertical 4.5 mm outside
- Readout
  - U-shaped 0.8 mm WLS fiber : 27,000 km!
  - APDs (80% QE)

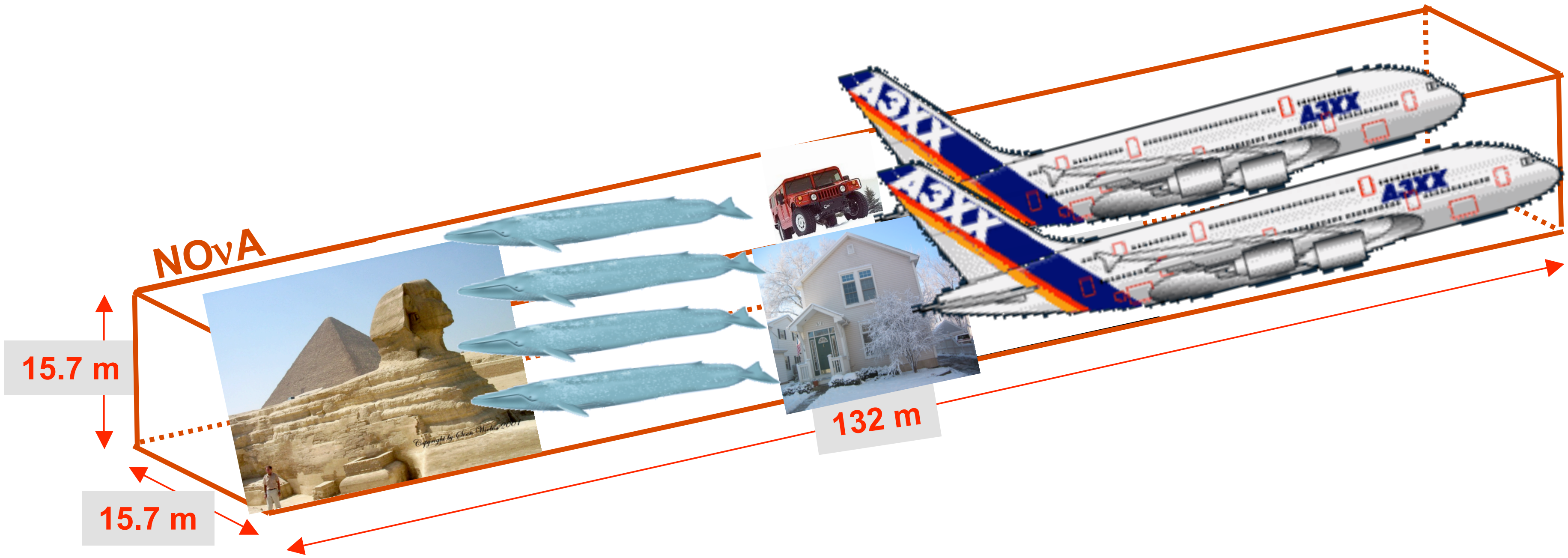




One Plane: 15K kg

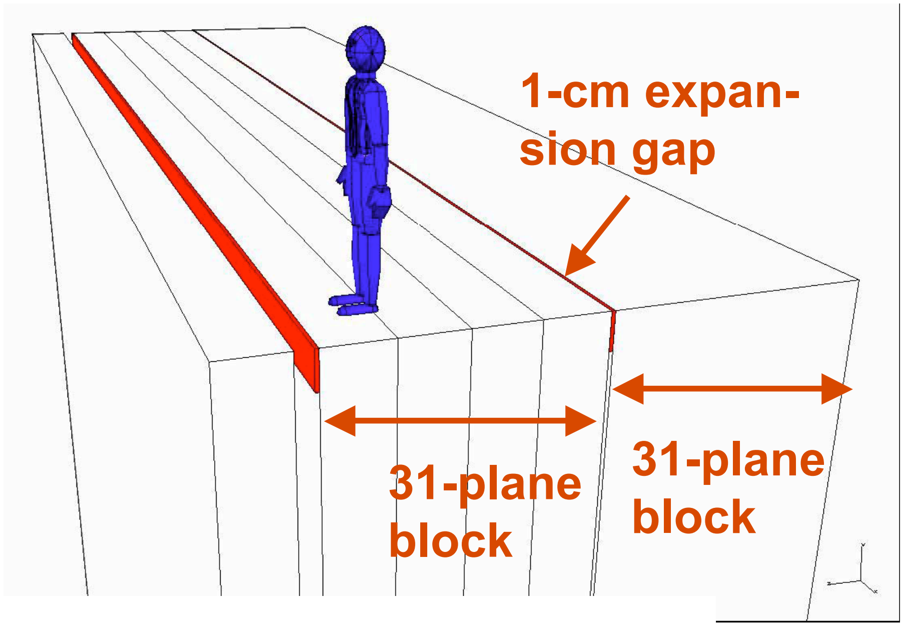
Horizontal/vertical cells different for structural strength

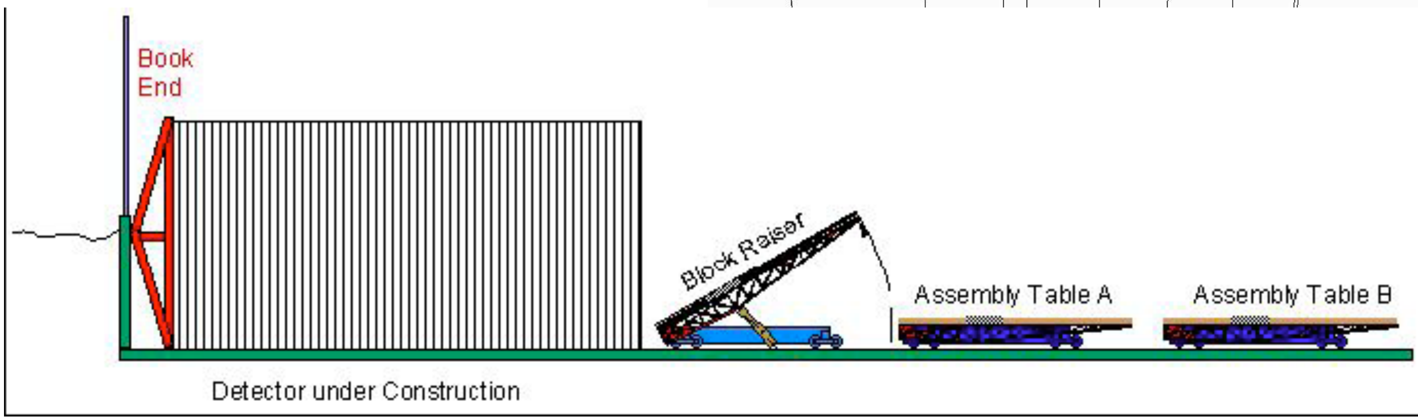
Just how big *is* That?



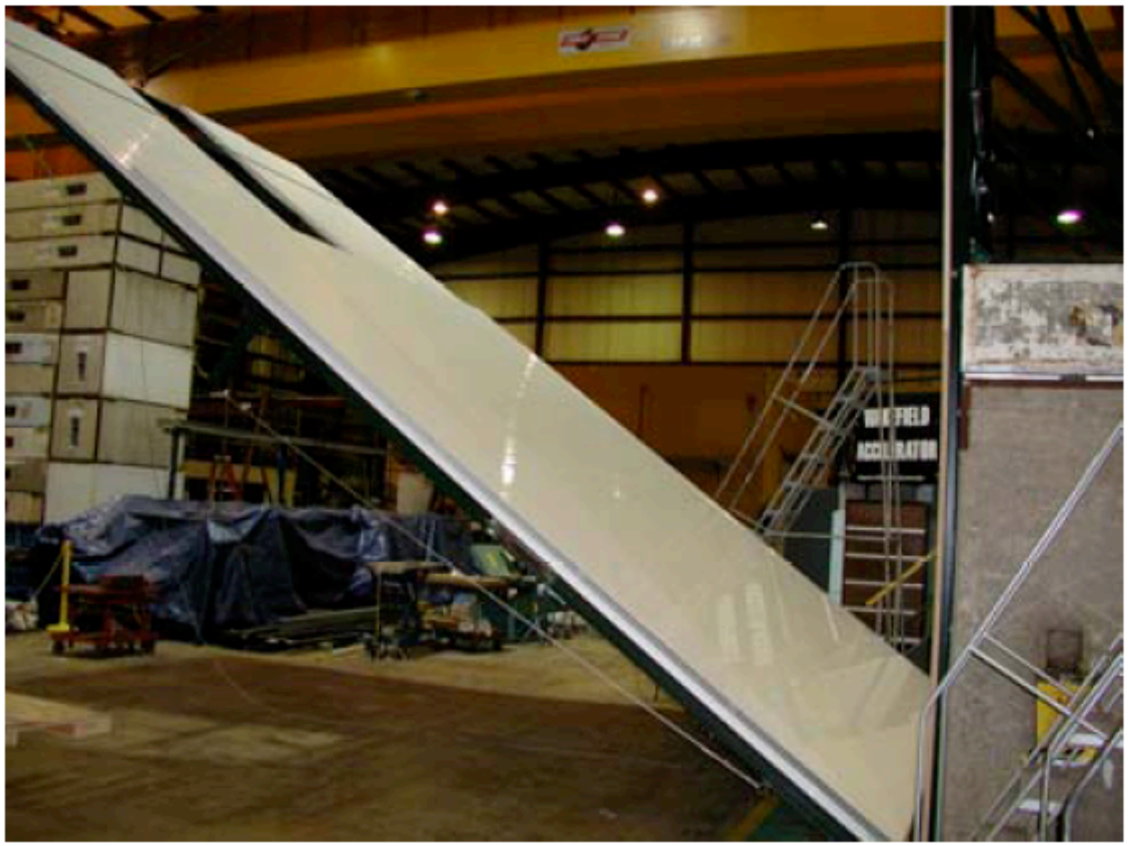
Far Detector Assembly

- Detector has 64 (31-plane) blocks
- Can fill with scintillator and run during construction
- Half-Size planes built & tested at Argonne



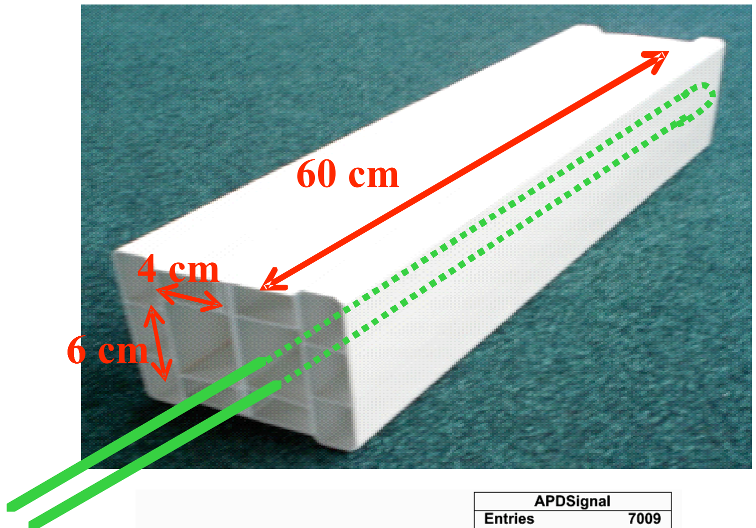


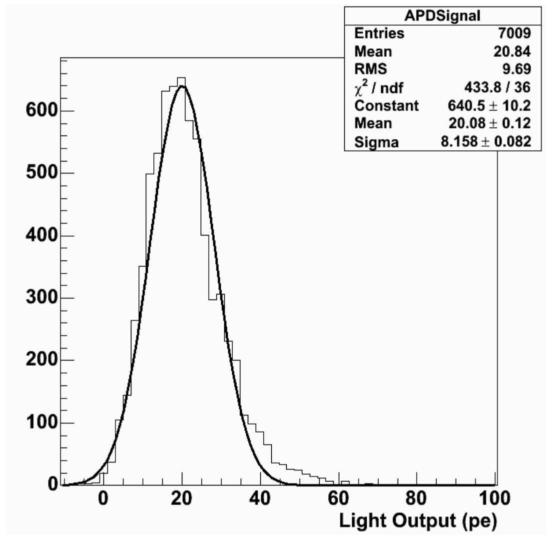
Half Block Prototype Being Built



Number of Photoelectrons

- Transverse Cell Dimensions the same
- Length of cell shorter but 33.5 meter fiber identical
- Read out to APD
- #PE stable over 2 months
- *Enough light!*

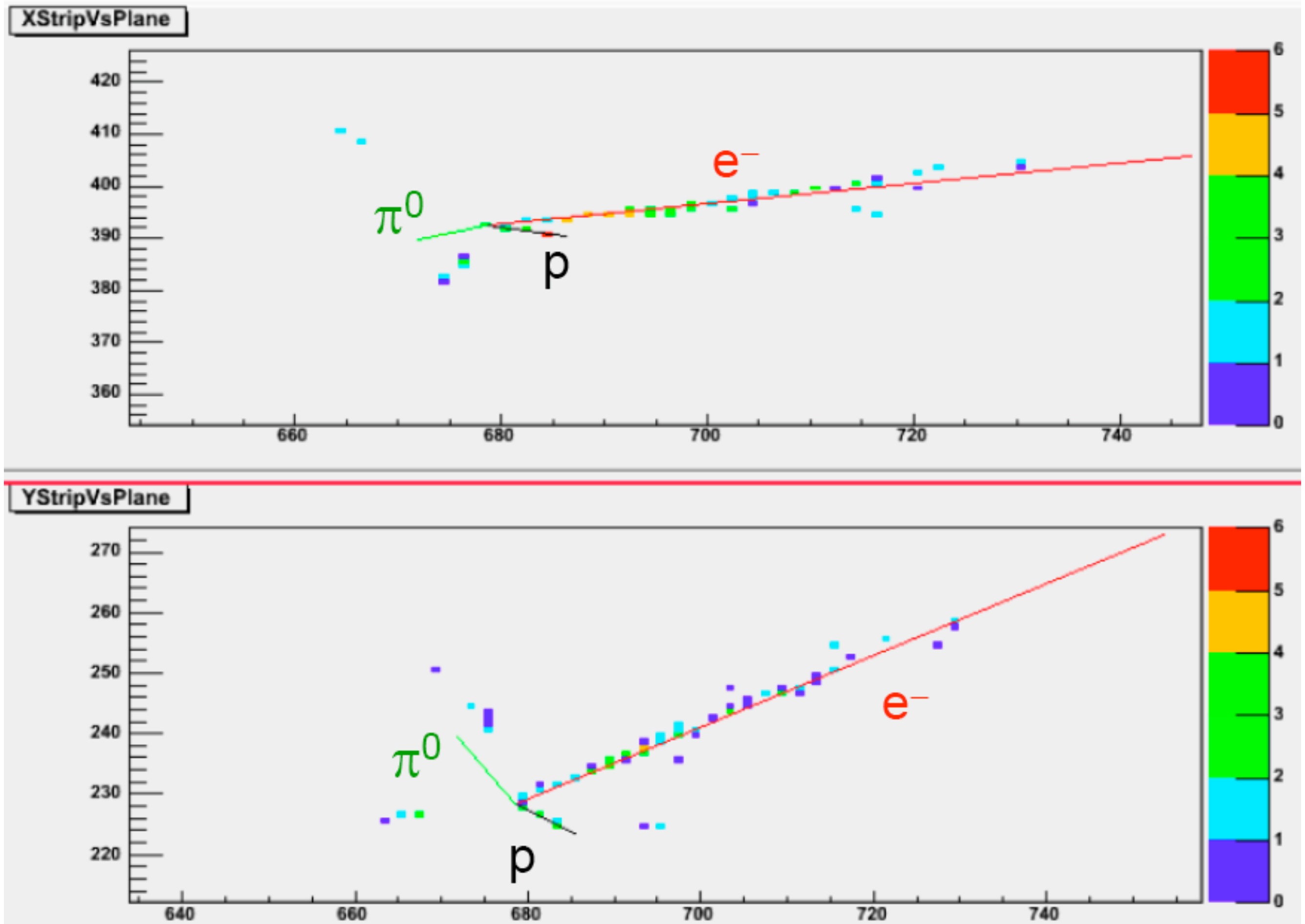




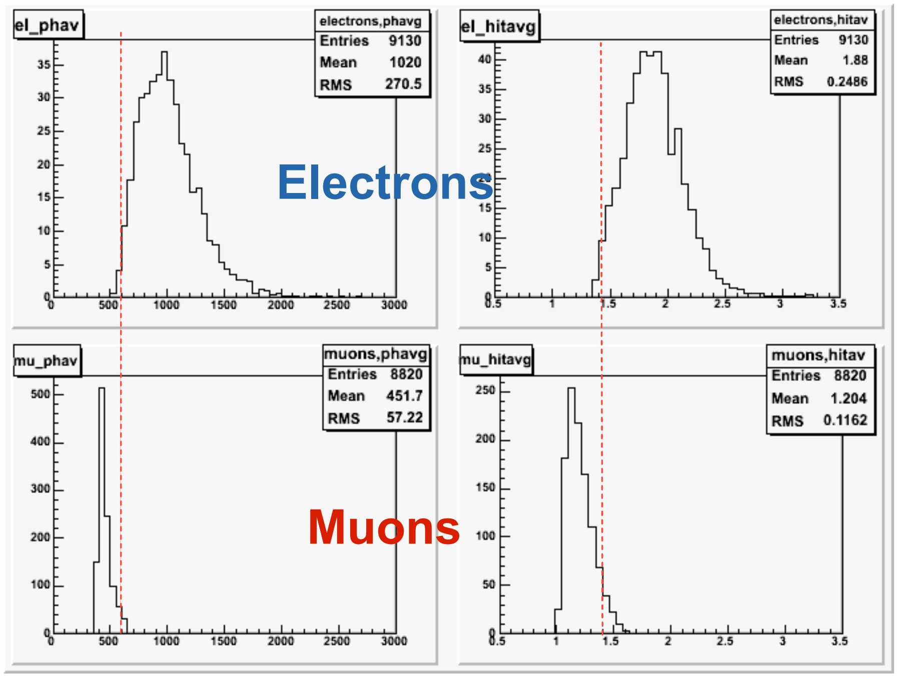
NOνA vs. MINOS for ν_e

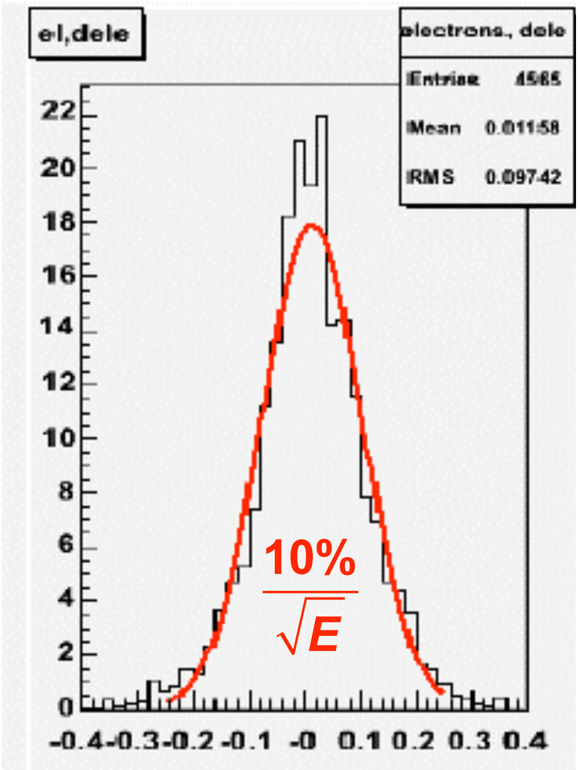
- Other than the off-axis beam…
  - Mass increased by a factor of 6
  - Improved energy resolution and e/π^0 discrimination
    - "Totally active scintillator detector" (TASD) instead of sampling calorimeter
    - Increase longitudinal sampling by a factor of 10 (1.5 X_0 to 0.15 X_0)
- All while reducing the cost/kiloton by a factor of 3 with respect to MINOS Far Detector
- No magnetic field in NOνA

Sample MC Event
1.65 GeV $\nu_e N \to e p \pi^0$



Electron ID & Energy Resolution





Electron resolution

Also use RMS of pulse height per plane, gaps & energy cuts

Reconstruction

Two Algorithms:using a maximum likelihood analysis with the following variables

a) Total measured energy
b) Fraction of total energy carried by the electron
c) Mean pulse height near the origin of the electron
d) Pulse height per plane for the electron
e) Number of hits per plane for the electron
f) Energy upstream of the vertex
g)Curvature of the electron
h) Missing transverse momentum
i) Fraction of total electron energy contained in the first half of the electron track
j) rms deviation of electron hits from the fitted track
k) number of tracks identified as hadrons in the event

Efficiency Typically 25-40%: Algorithms under development

FOM = Signal/Sqrt(Bkg)

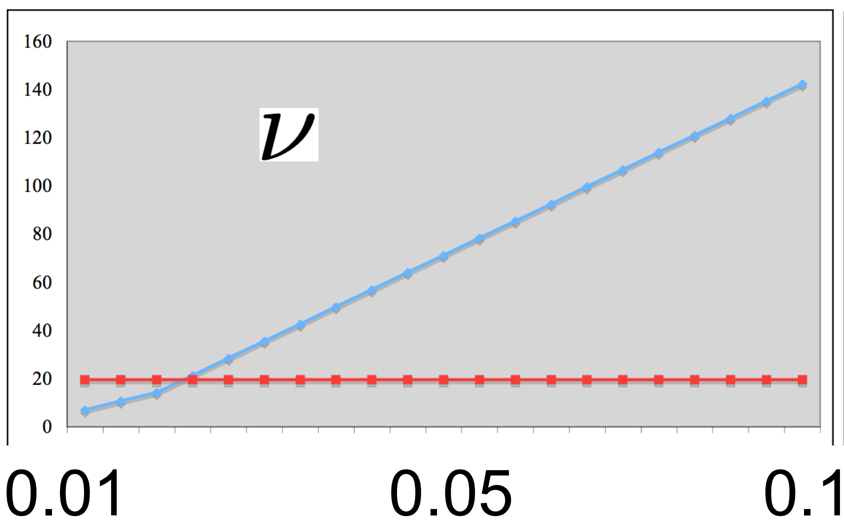
Cell width	Cell Depth	Relative FOM	Electron Energy
3.8	4.5	1.0	10.0%
3.8	6.0	1.02	10.7%
5.4	4.5	0.9	9.9%

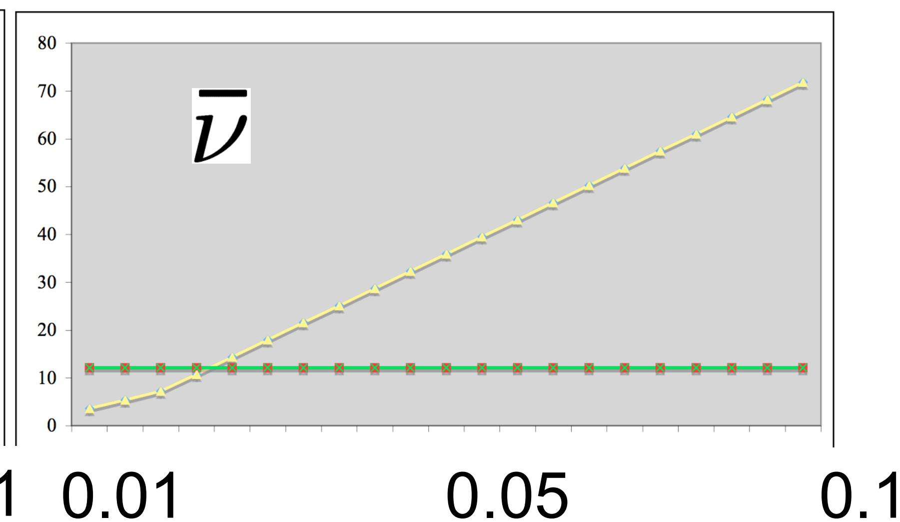
Tradeoffs

- Primary problem is tradeoff between acceptance and background rejection:
  - E.g. $$\pi^0 \rightarrow \gamma\gamma \rightarrow \text{electrons}$$
  - Look for "gap" from photons at beginning, followed by shower
  - Tradeoff of acceptance vs. shower fluctuations vs. background rate and ability to accurately model
  - Beam-Related backgrounds are measurable and small
- Lots to do, progress being made

Signal and Backgrounds

- Statistical Power: why this is hard and we need protons





For $\sin^2 2\theta_{13} = 0.1$:

ν: S=142.1, B=19.5

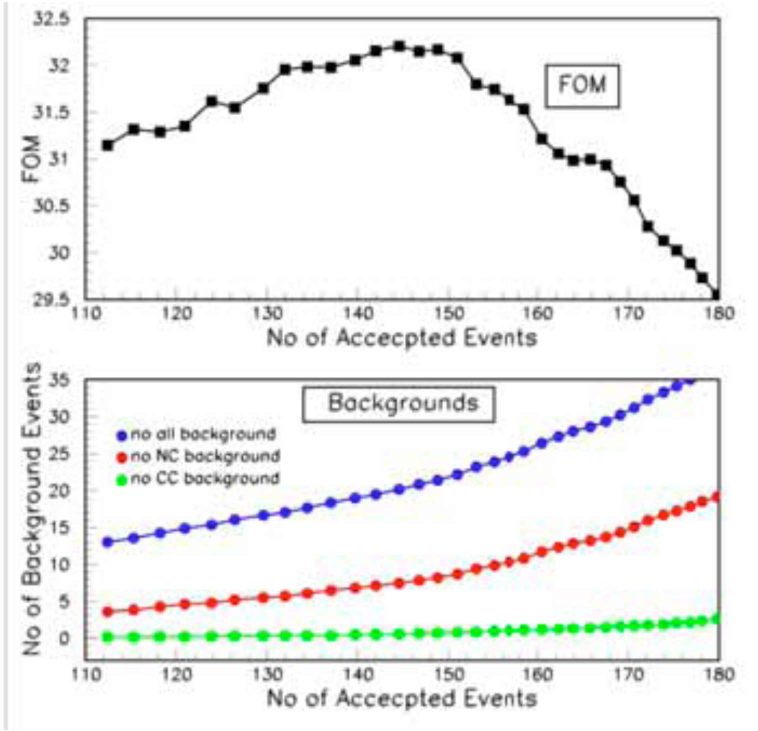
$\bar{\nu}$: S= 71.8, B=12.1

5 yrs at 6.5E20 pot/yr, efficiencies included

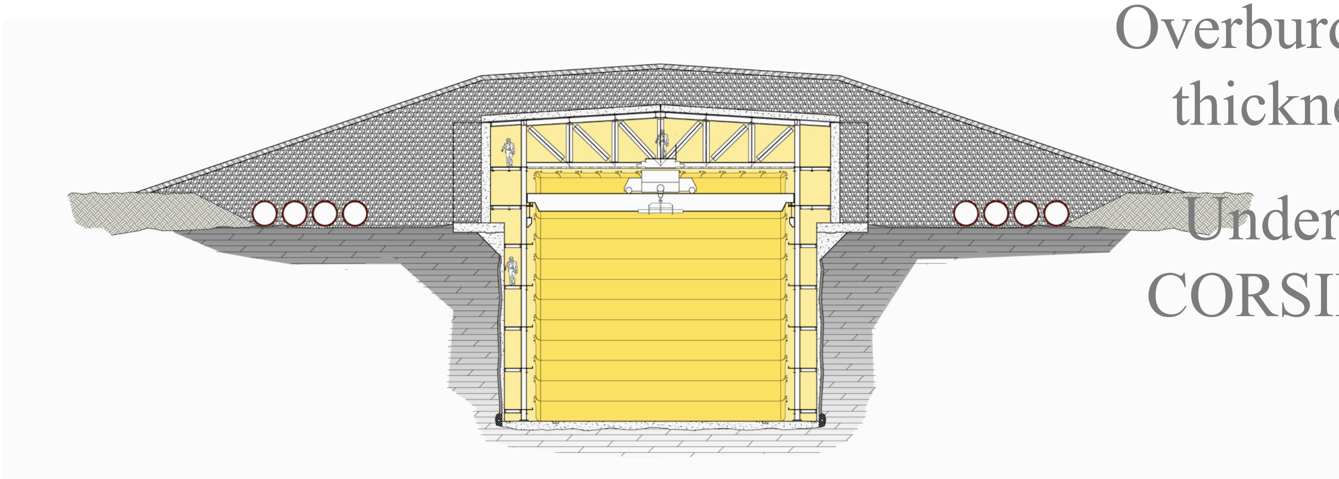
Sensitivity to Reconstruction Cuts

- Vary cut on likelihood function
- What Happens to Signal/Sqrt(Bkg) = FOM
- What happens to rates?

- *Nothing drastic*
- *Very much under development, but we're thinking about this and the numbers are reasonable*

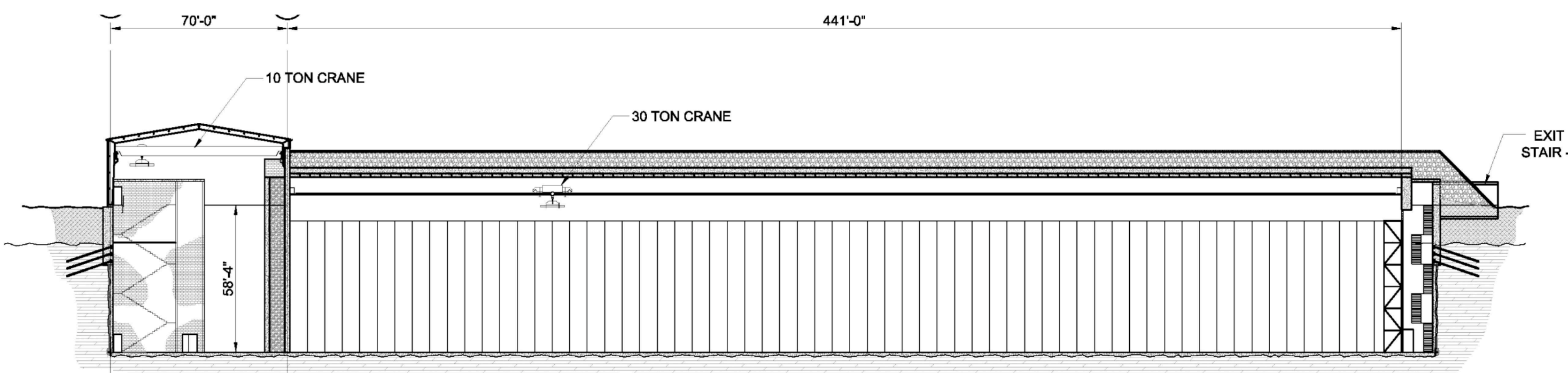


Far Detector Building Design with Overburden

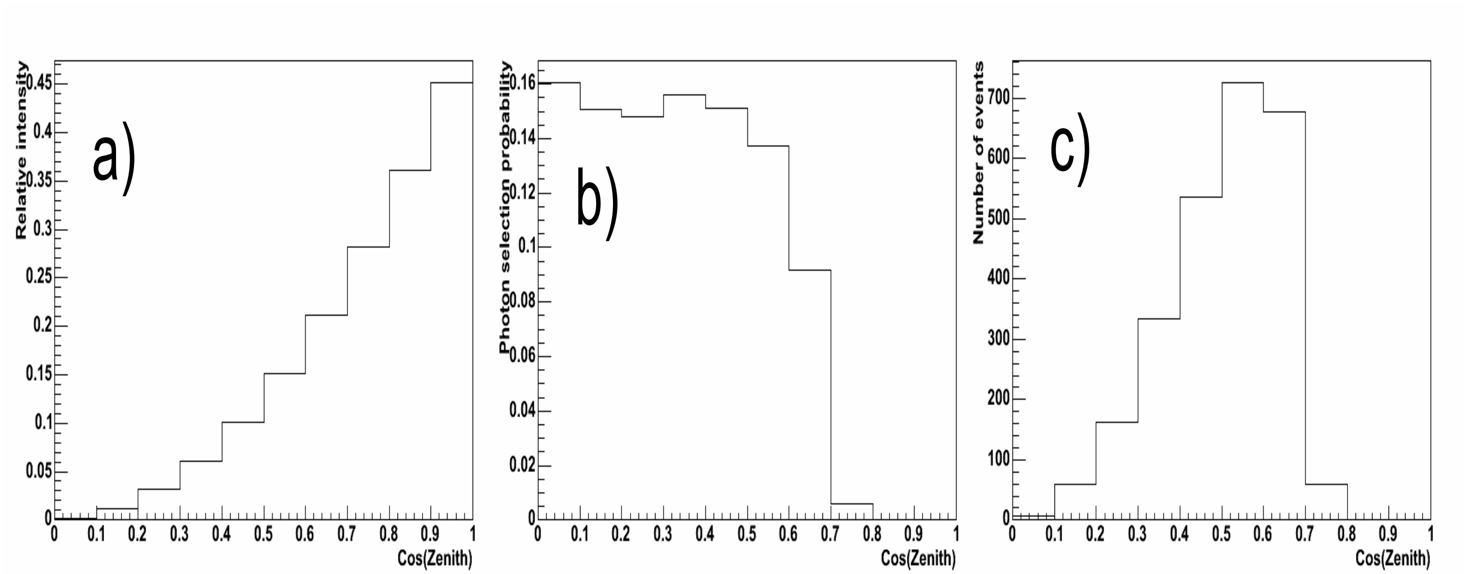


Overburden:Minimum thickness possible

Under study with CORSIKA/GEANT



Determination of Overburden

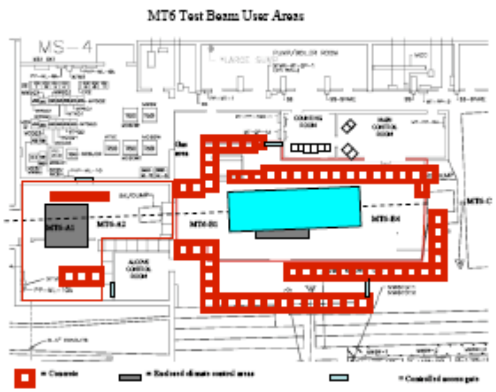


a) Incident Rate
b) Probability
c) Convolution

γ-flux is source of bkg:
needs to come in at angle
to look like signal

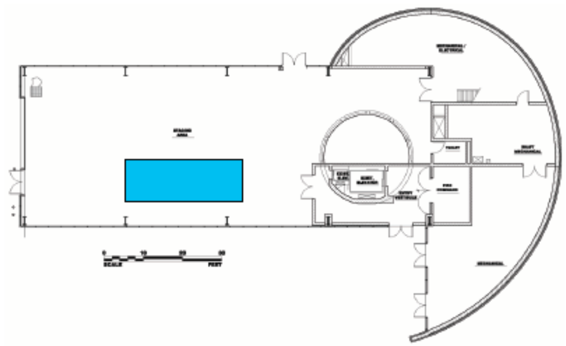
Need 2 m overburden to eliminate

Near Detector: Modular & Mobile



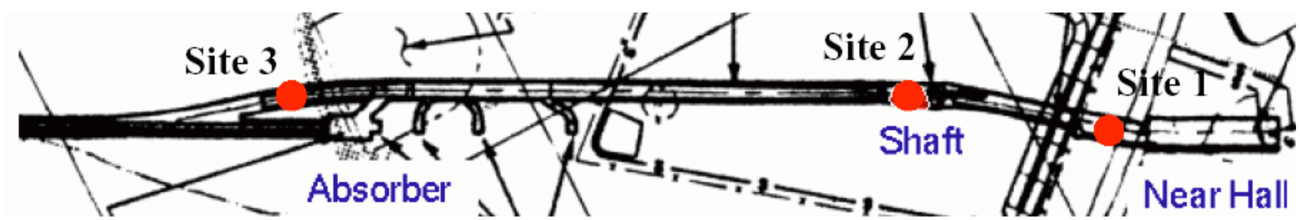
M Test

Calibrate in Test Beam



MINOS Surface Building

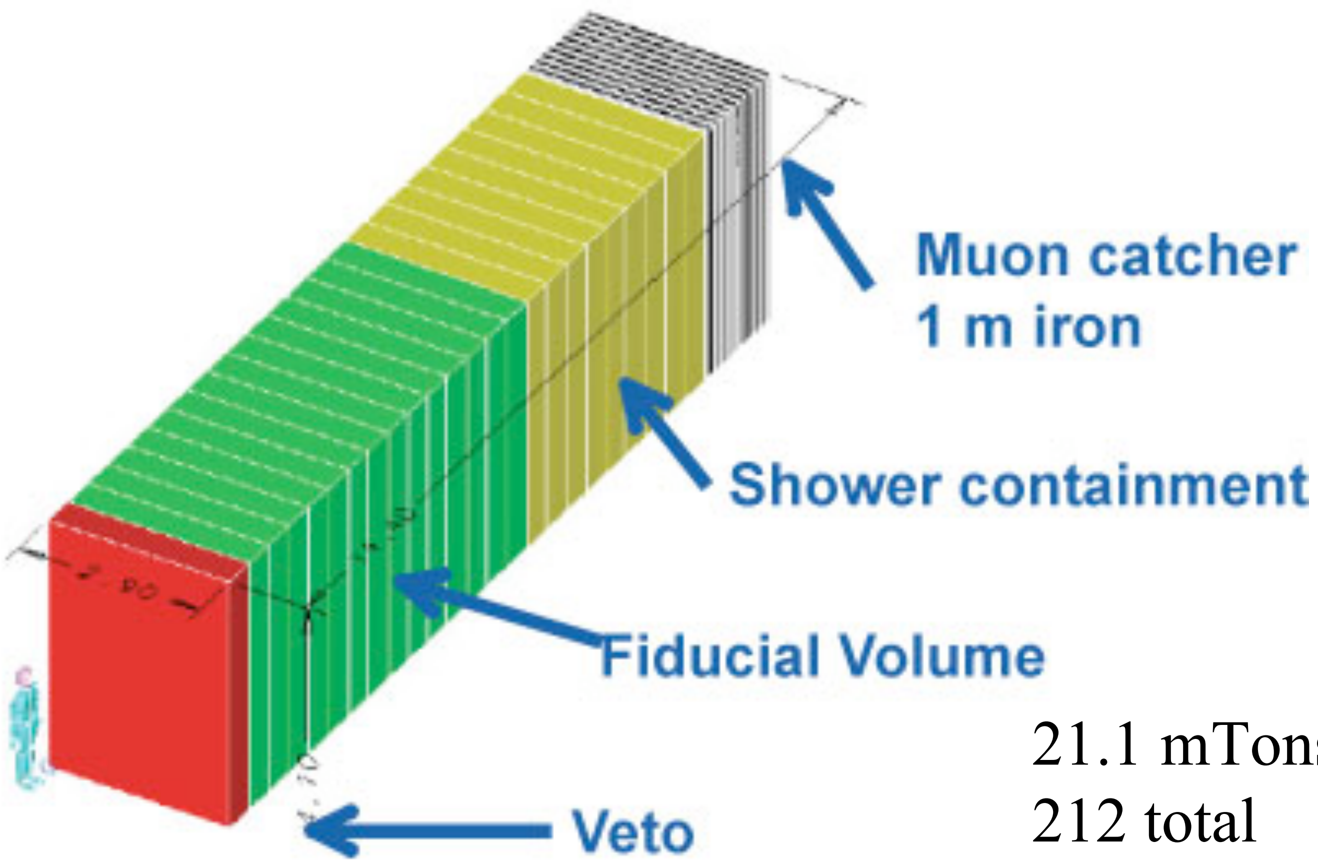
Response to ν_μ and ν_e



NuMI Access Tunnel

Measure Beam Properties

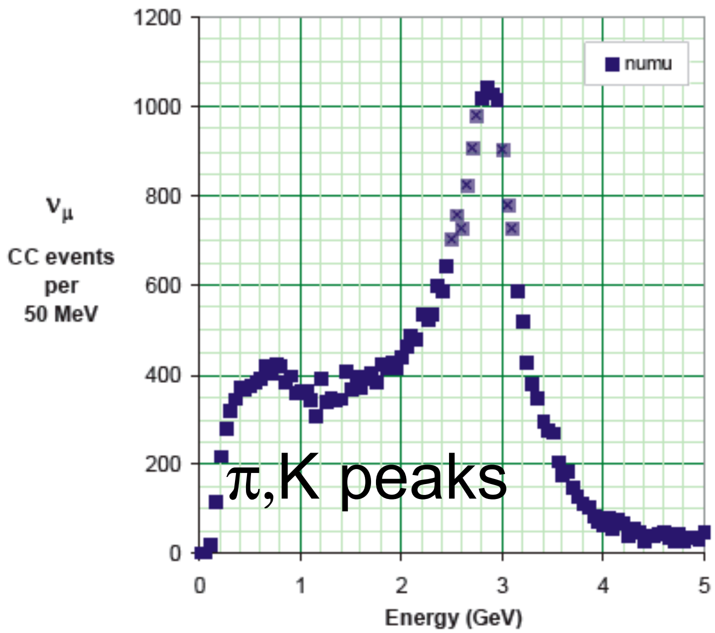
Near Detector

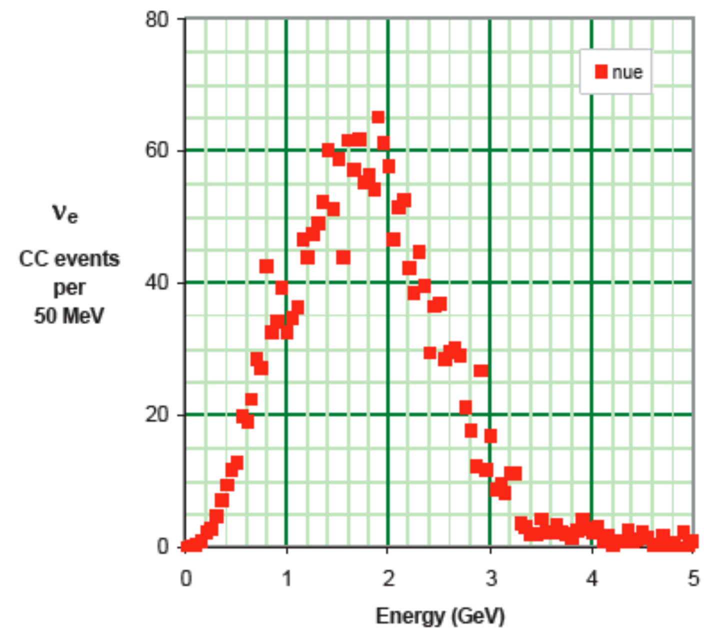


21.1 mTons fiducial
212 total
3.2 events/pulse

Surface Measurement

6.5 x 10^{20} pot in 75 mrad off-axis beam





Far Data Spectrum peaked at 2 GeV

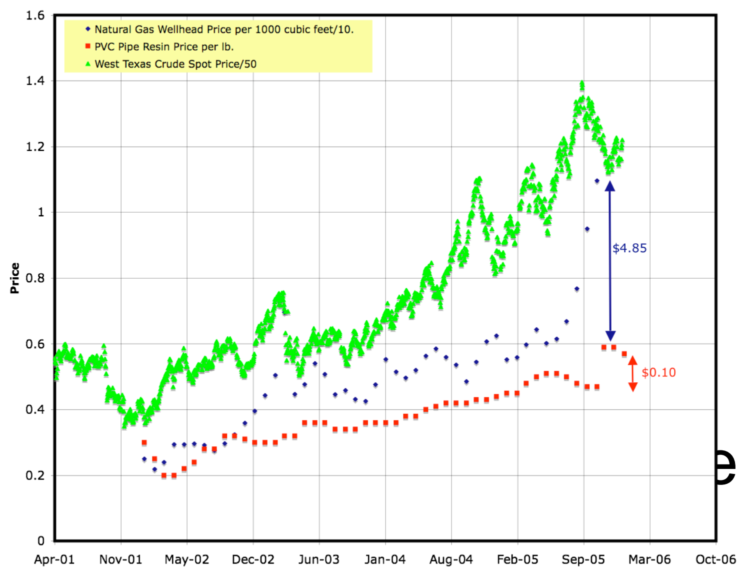
Cost

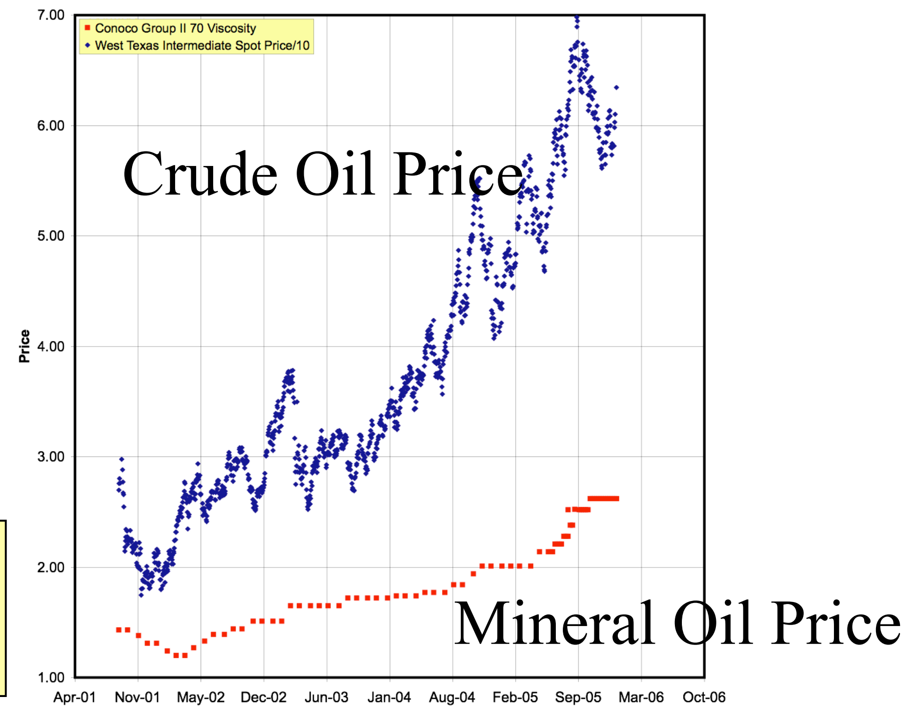
	Contingency	Total Cost M$
Far Detector		
Active detector	30%	80
Electronics and DAQ	55%	13
Shipping	21%	7
Installation	43%	14
Near Detector	44%	3
Building and outfitting	58%	29
Project management	25%	5
Additional contingency		14
Total	50%	165

- Sensitive to price of crude oil!
  - We have understanding of how price depends on petroleum price: can make sensible estimates

Sensitivity to Petroleum Price

PVC resin increases ~ $0.03/lb. for every $10/barrel increase in the cost of crude oil.





Mineral oil increases ~$0.03/gal for every $1.00 increase in the cost of crude.

Proton Intensity

- NOνA will run after the Tevatron terminates operation. Thus, parts of the accelerator complex now devoted to antiproton production and storage will be available for the neutrino program.
- Assumption of our proposal:
  - 0.7 MW, of which we assumed 0.625 MW for the NOνA program. (for no proton driver)
- Fermilab strategy:
  - If ILC looks affordable, move to host the ILC and do "cheap" upgrades to the proton intensity.
  - If ILC will be delayed, move toward a Proton Driver

    (i.e., a new Booster).
- We assume that the Proton Driver will allow 2.4 MW.

Schedule

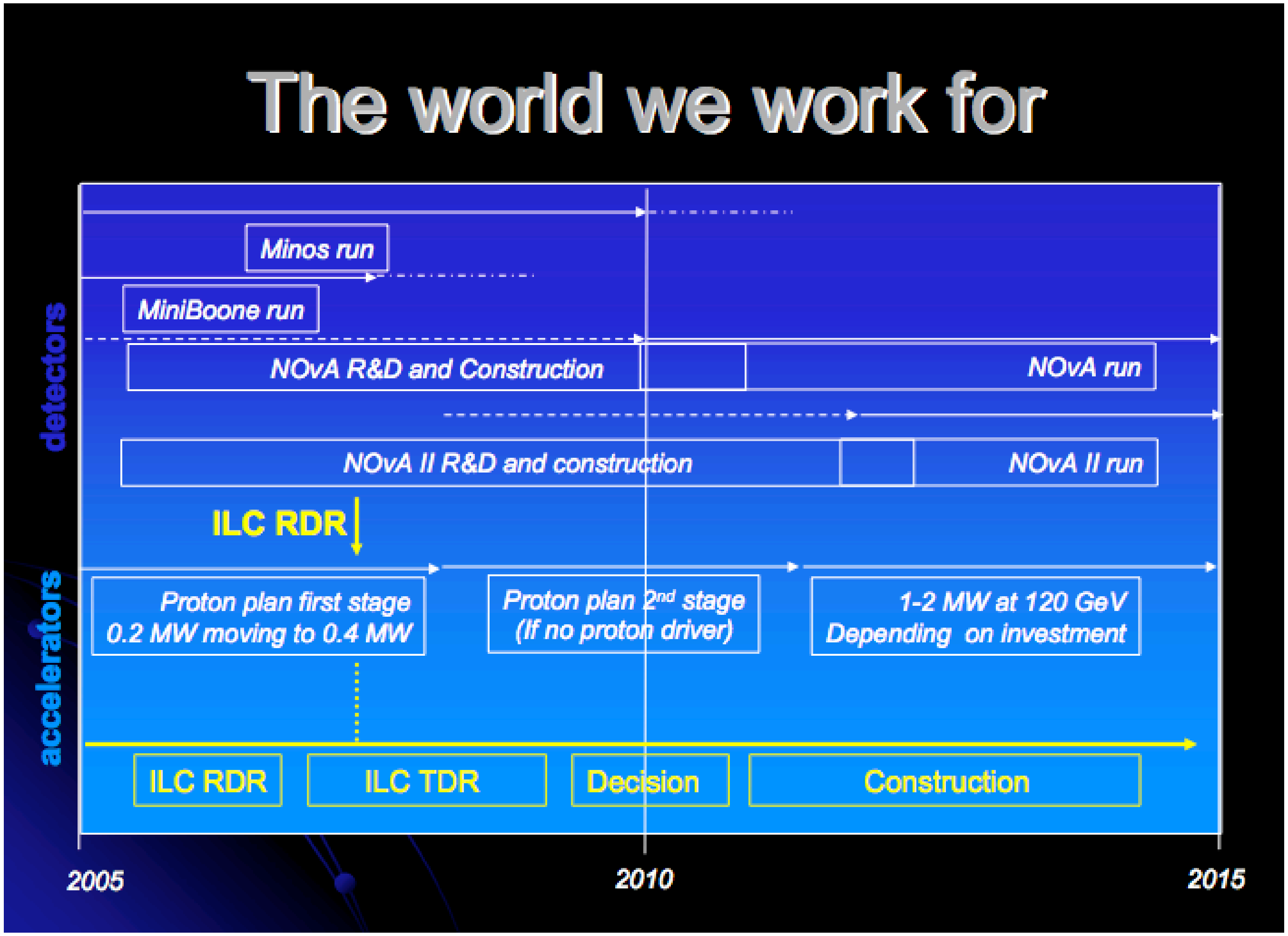
- Cannot start in FY2007 due to regulations on Congressional line items.
- Aiming for a FY2008 project start.
- Start of data taking October 2010
- Completion of the Far Detector July 2011

3 Feb 06: President's Budget: White House to Congress
High Energy Physics Program ($775.1 million)
This is a $58.4 million increase over FY 2006.

!!!!

Project engineering and design funding of $10.3 million is requested for the new Electron Neutrino Appearance project.

From Oddone to EPP2010



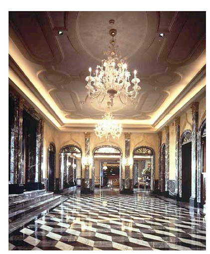
Conclusions

- The Fermilab/NuMI/NOνA program provides a flexible, step-by-step approach:

Mass Hierarchy
(leaving, not coming in!)

Gateway to Paradise: $\sin^2 2\theta_{13}$

Ghiberti's Gates of Paradise in Firenze



$\Delta m^2_{23}, \theta_{23}$

CP δ

$\mathcal{O}$(2800 kg Au in mosaics)